High energy, single-mode, all-solid-state Nd:YAG laser

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Laser Risk Reduction Program (LRRP)

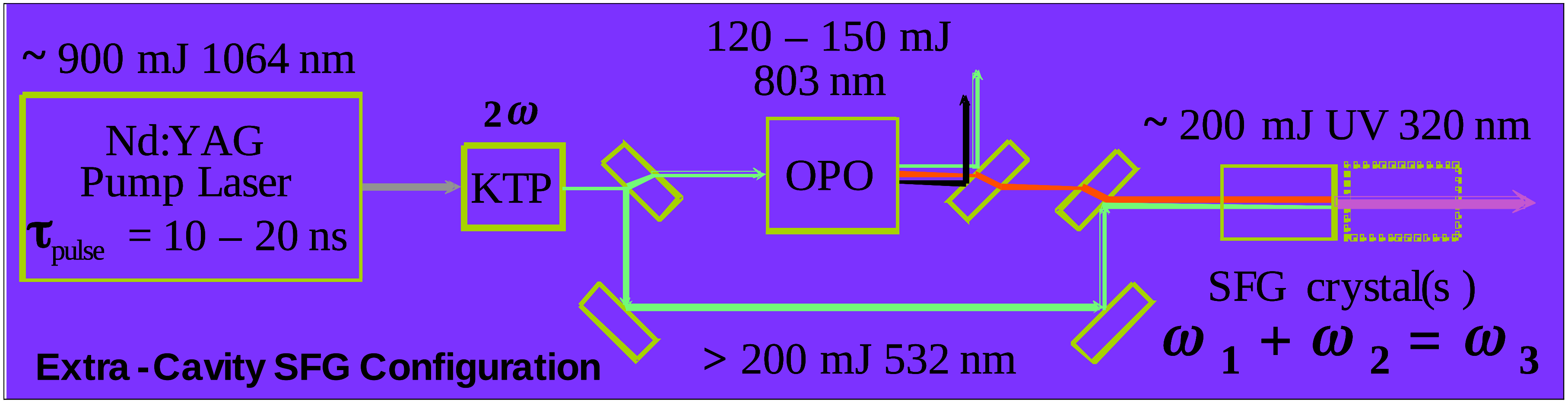
- **NASA began Laser Risk Reduction Program (LRRP) in 2002 to develop reliable, robust, and compact laser technologies based lidar applications for space based platforms**
  - ***Programmatics:*** **LRRP is a joint operation of Langley Research Center and Goddard Space Flight Center**
  - ***Goal*****: To advance 1 micron and 2 micron lasers and associated wavelength conversion technology**
  - ***Applications:*** **Four Lidar techniques-altimetry, Doppler, Differenctial Absorption Lidar (DIAL), backscatter lidar**
  - ***Technical Objectives:*** **6 priority Earth Science measurements-**
    - **Surface and ice mapping**
    - **Horizontal vector wind profiling**
    - **Carbon-di-oxide (CO_2) profiling**
    - **Ozone (O_3) profiling**
    - **Aerosol/clouds**
    - **River currents**

DIAL based Ozone profiling from space based platforms

- **The objective of the UV Task: To develop an efficient, all-solid-state, diode pumped, conductively cooled, single longitudinal mode and high energy 1-micron to UV wavelength conversion technology to generate UV wavelengths of 308 nm and 320 nm**
- **Performance Goals:**
  - Output energy at UV wavelengths: ≥ 200 mJ/pulse
  - Pulsewidth: 10 - 25 ns
  - PRF: 50 Hz
- High pulse energy allows enhanced performance during strong daylight conditions
- UV Task is a collaborative effort among Sandia National Labs, Fibertek, and NASA LaRC

Technical Approach

- Feasibility of approach established -



- **A conductively cooled, >1 J/pulse, single mode Nd:YAG pump laser is coupled to an efficient RISTRA OPO and SFG assembly**

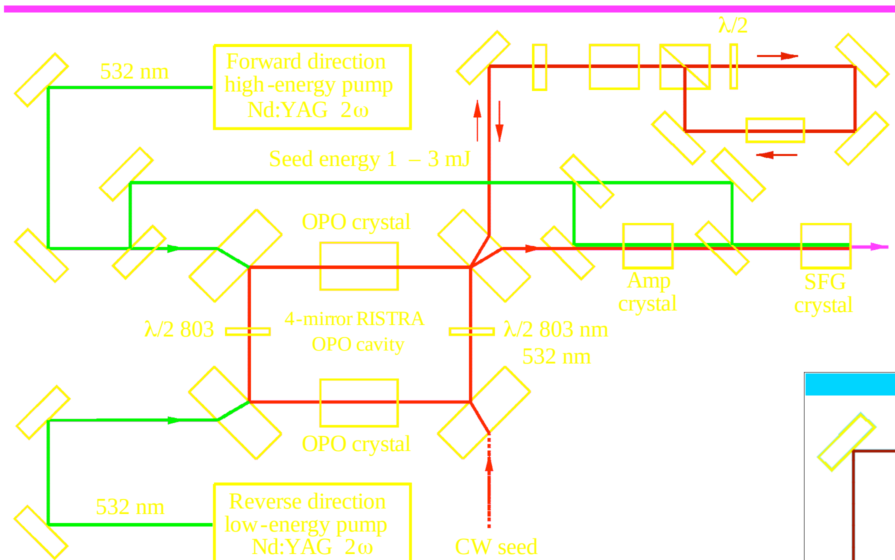
- **The technological feasibility of UV generation using flash lamp pumped Nd:YAG laser coupled to two types of nonlinear optics arrangements has been demonstrated**

  – **The current status of the solid-state pump laser is reported**
  – **A compatible compact UV transmitter brassboard is being developed**

Test Configurations for UV Generation

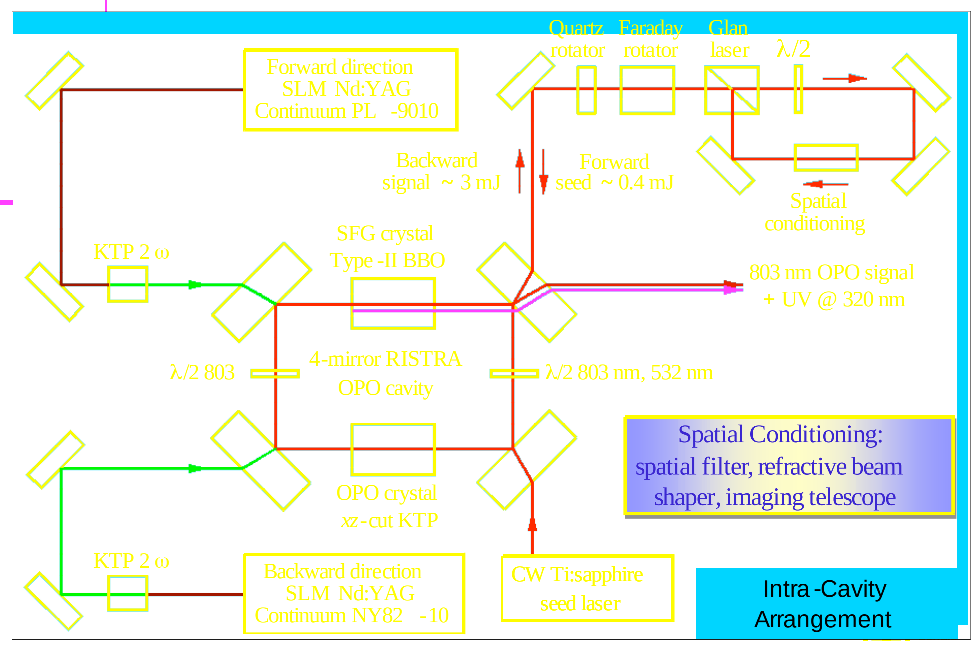
-Technology Demonstration has been successful-

Extra-Cavity SFG Setup



At 320 nm, up to 200 mJ extra-cavity SFG IR to UV efficiency > 21% (> 27% for 1 mJ seed)

Intra-Cavity SFG Setup

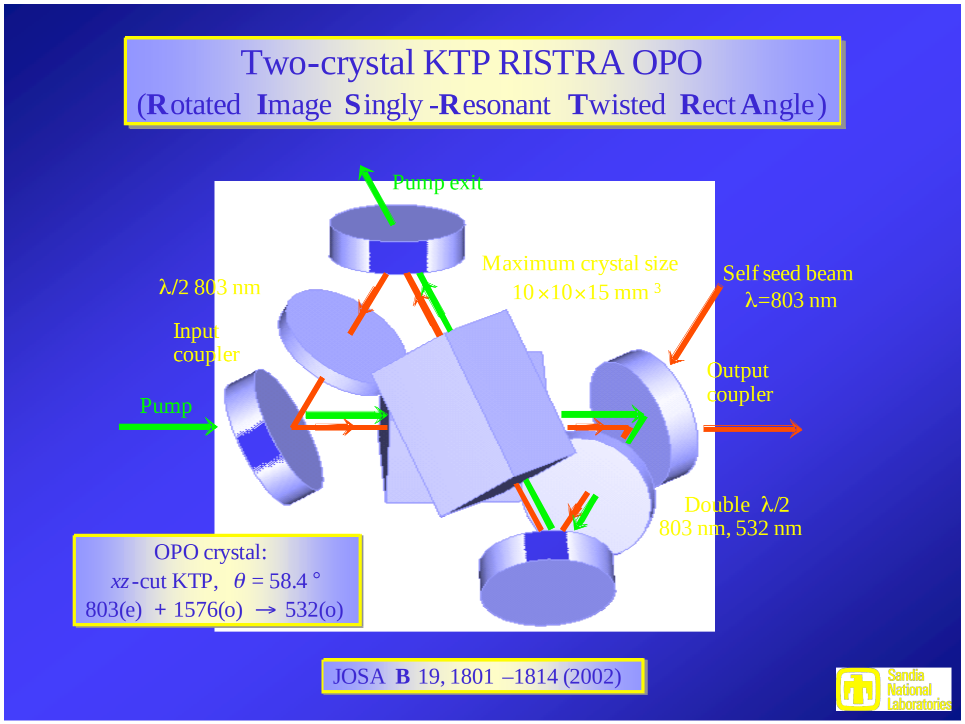


At 320 nm , up to 160 mJ intra-cavity SFG IR to UV efficiency up to 24%

Fluence ≤ 1 J/cm2 for most beams

RISTRA OPO

-A technology developed at Sandia National Labs-



Compact assembly

Four-mirror image-rotating non-planar ring resonator

No alignment

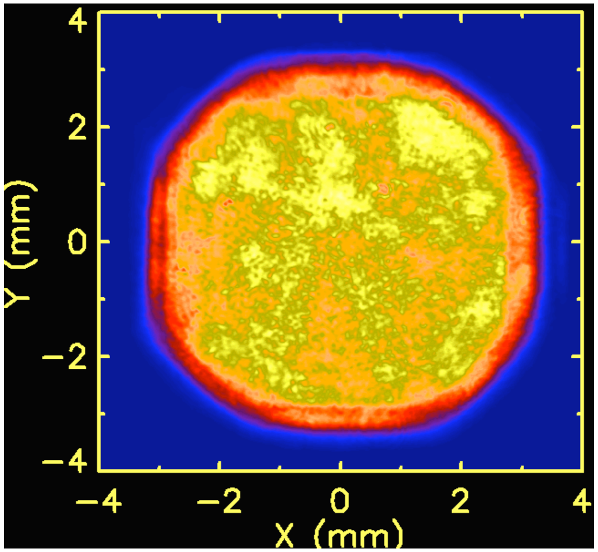
Long term stability

Good beam quality

Image-rotating RISTRA Performance

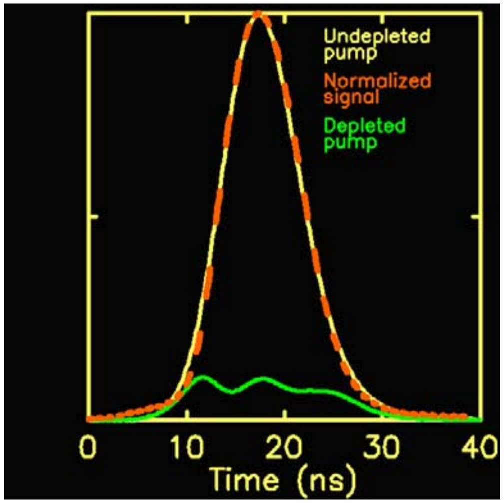
-Spatial fluence profiles and pump depletion-

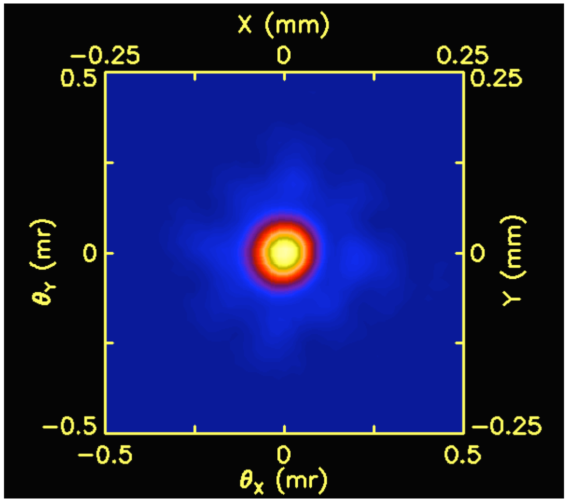
Flat pump profiles have facilitated high OPO conversion with good beam quality



OPO signal near-field spatial fluence profile, Fresnel Number > 450

Illustration of self-seeded oscillation in two-crystal RISTRA
~85% pump depletion;
Currently >90%



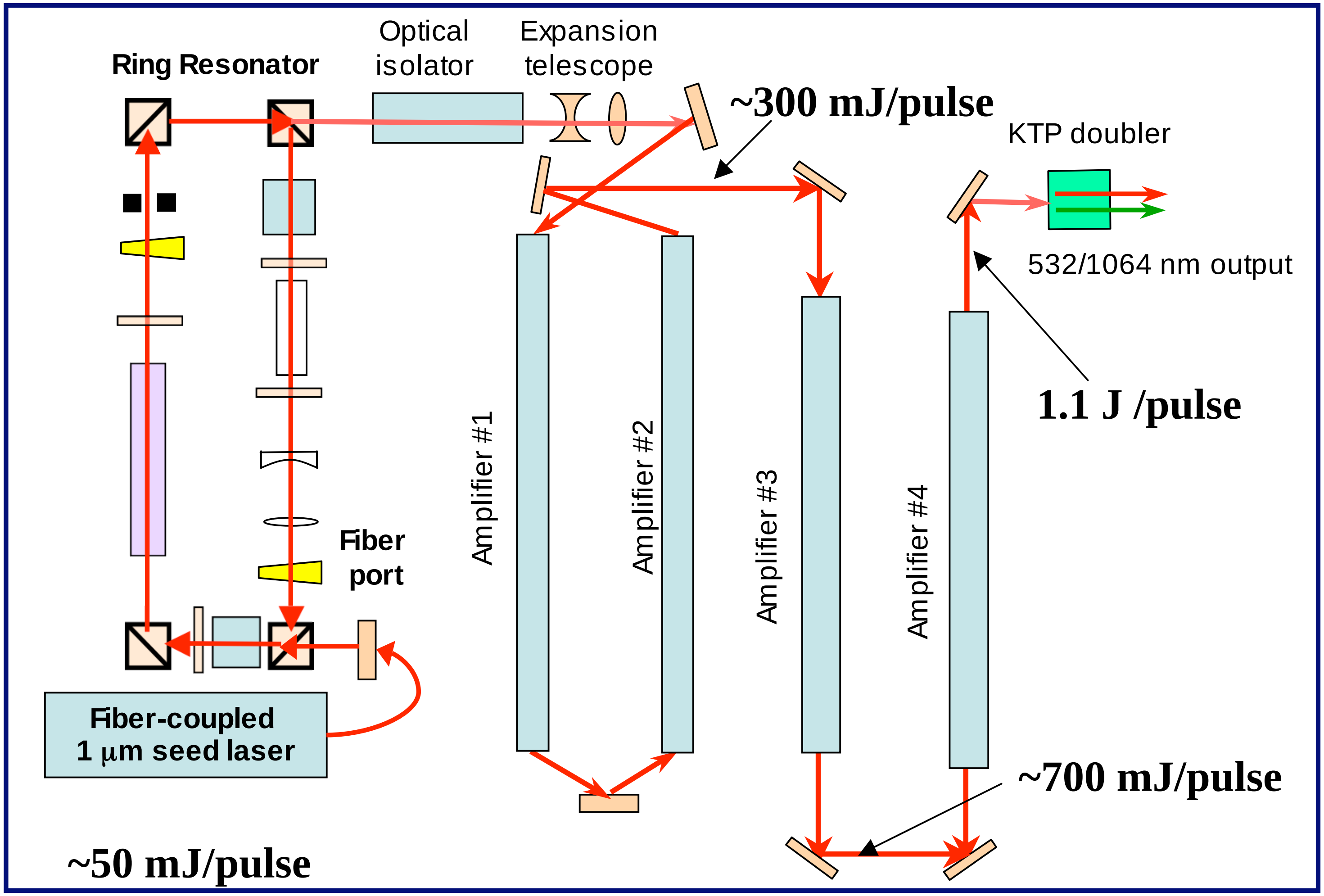


OPO signal far-field spatial fluence profiles, Fresnel Number > 450

Diode-pumped >1 J Nd:YAG Pump Laser

-Master Oscillator Plus 4 Amplifiers-

Final System Optical Configuration with accomplished output pulse energies



Nd:YAG Pump Laser

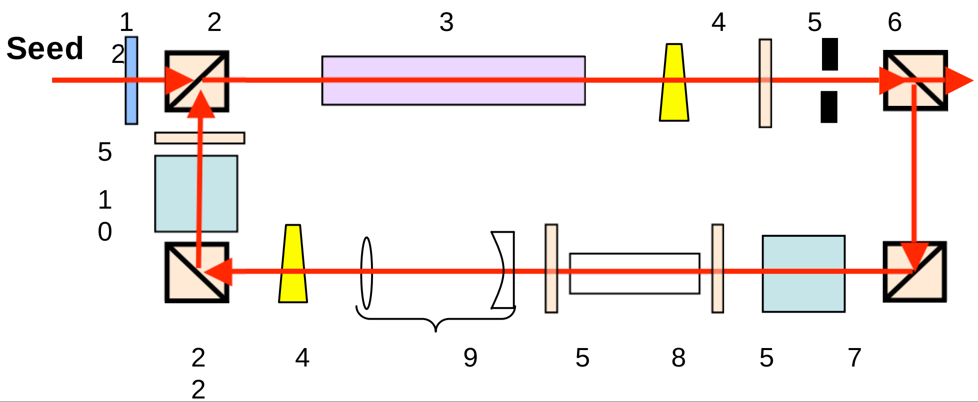
-Summary of Technical Approach-

Features of an all solid-state diode-pumped laser transmitter:

Injection seeded ring laser	**Improves emission brightness (M^2)**
Diode-pumped zigzag slab amplifiers	**Robust and efficient design for use in space**
Advanced E-O phase modulator material	**Allows high frequency cavity modulation for improved stability injection seeding**
Alignment insensitive / boresight stable 1.0 μm cavity and optical bench	**Stable and reliable operation over environment**
Conduction cooled	**Eliminates circulating liquids w/in cavity**
Space-qualifiable component designs	**Establishes a path to a space-based mission**

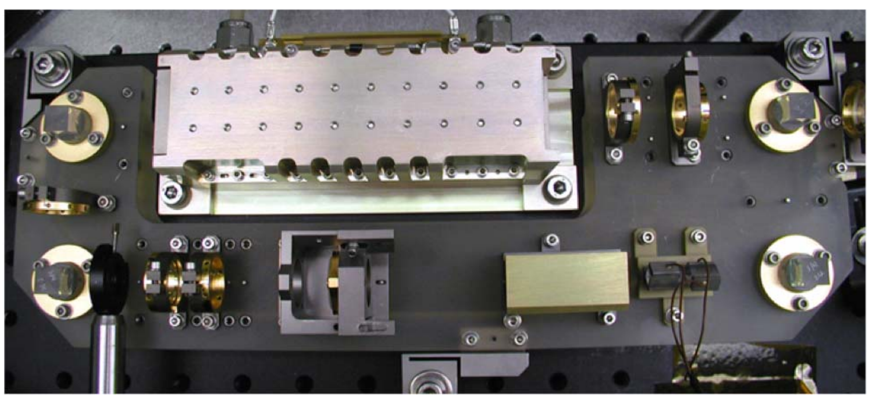
Single Frequency Laser Ring Laser Design

Optical Schematic



1. **Reverse wave suppressor**
2. **Cube polarizer**
3. **Odd bounce slab**
4. **Steering wedge**
5. **$\lambda/2$ waveplate**
6. **Mode limiting aperture**
7. **RTP phase modulator**
8. **45° Dove prism**
9. **Non-imaging telescope**
10. **RTP q-switch**

Final Zerodur Optical Bench (12cm x 32cm)



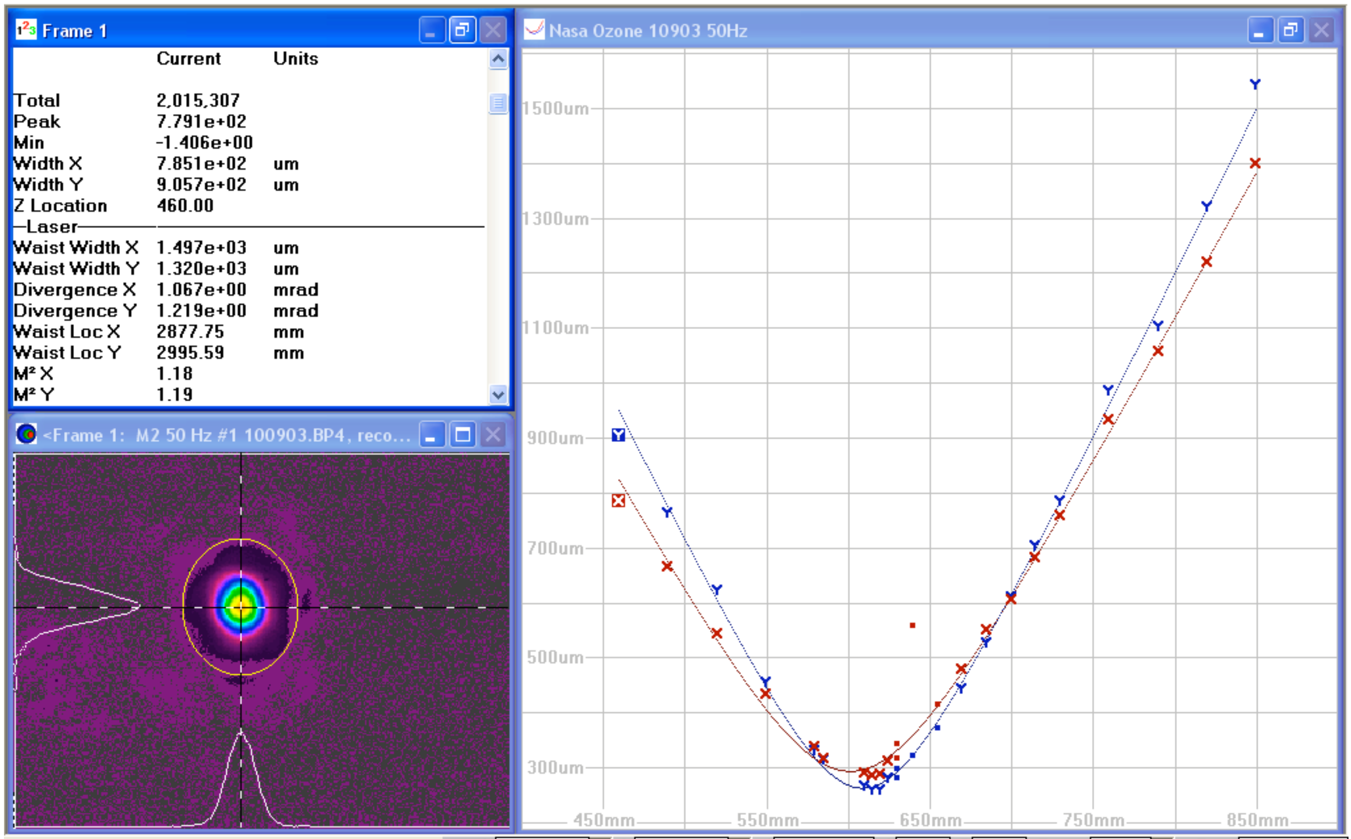
Design Features

- Near stable operation allows trading beam quality against output energy by appropriate choice of mode limiting aperture
  - –30 mJ TEM_{00}, M^2 =1.2 at 50 Hz
  - –30 mJ TEM_{00}, M^2 =1.3 at 100 Hz
  - –50 mJ square supergaussian, M^2 = 1.4 at 50 Hz
- Injection seeding using an RTP phase modulator provides reduced sensitivity to high frequency vibration
- PZT stabilization of cavity length reduces sensitivities to thermal fluctuations
- Zerodur optical bench results in high alignment and boresight stability

Ring Oscillator Performance

50 Hz TEM_{00} Oscillator Beam Quality Measurements

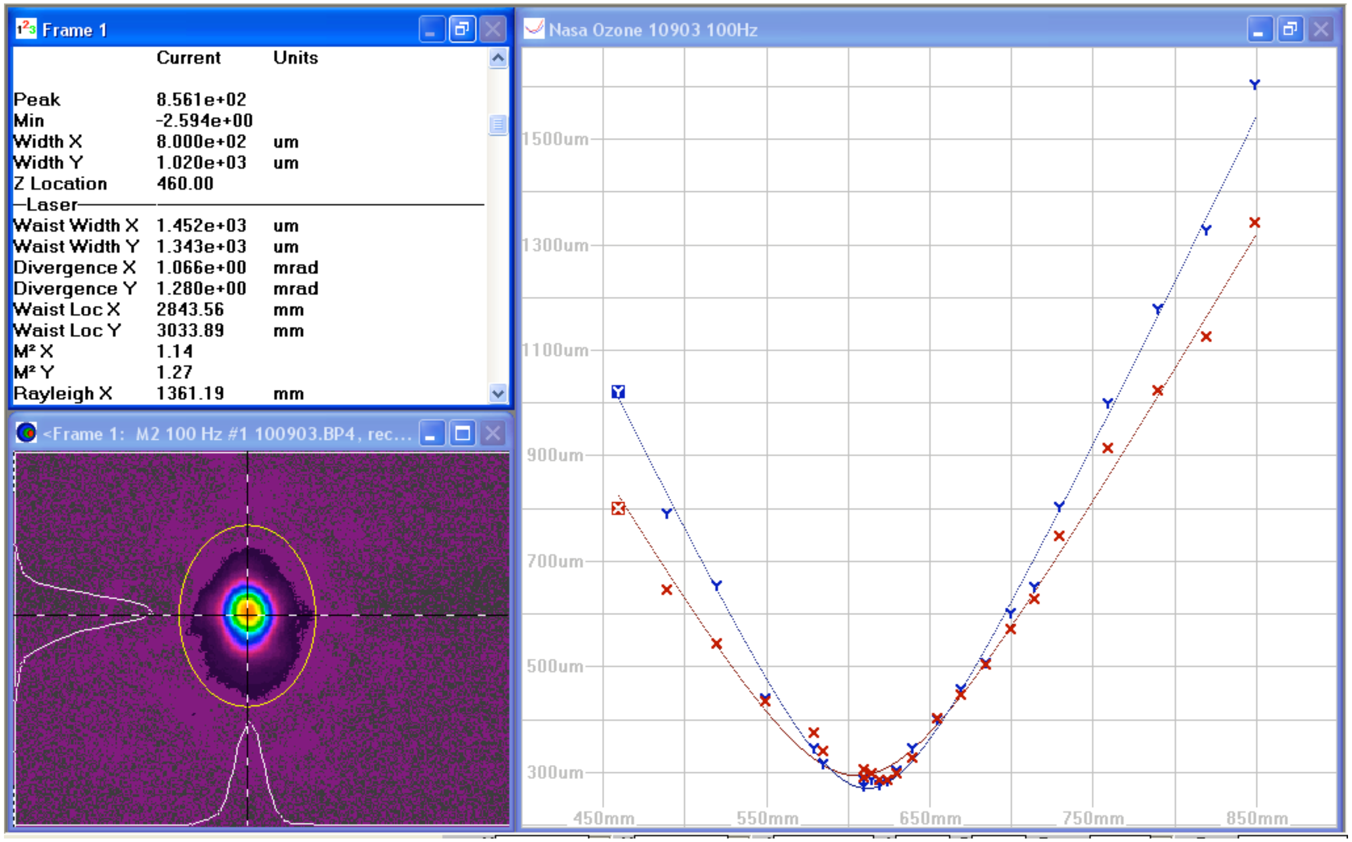
M^2 was 1.2 in both axes at an output energy of 30 mJ/pulse



Ring Oscillator Performance

100 Hz TEM_{00} Oscillator Beam Quality Measurements

M^2 was 1.2 in non-zigzag axis, 1.3 in zigzag axis at an output energy of 30 mJ/pulse



2-Sided Pumped & Cooled Amplifier

Dual Stage Amplifier Modeling

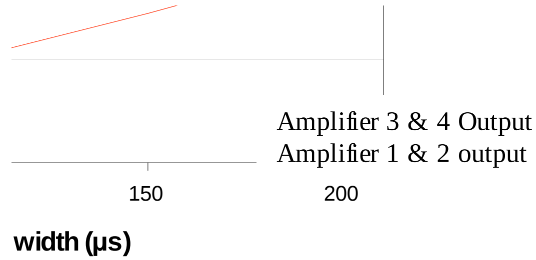
Model is based on Franz-Nodvic result for a amplifying a square (in time) pulse

Model includes all key parameters explicitly

- Number of pump diodes (192=12 ea. x 16 bars)
- Peak diode power (75 W)
- Diode pulse width
- Input oscillator pulse energy (60 mJ)
- Input beam diameter
- Gain path length in amp
- Slab volume

Accounts for reduced gain for second pass

1 J per pulse output is predicted for 210 µs diode pump pulses



Modeled output of dual 2 -sided pumped and cooled amplifiers for 60 mJ input to first stage

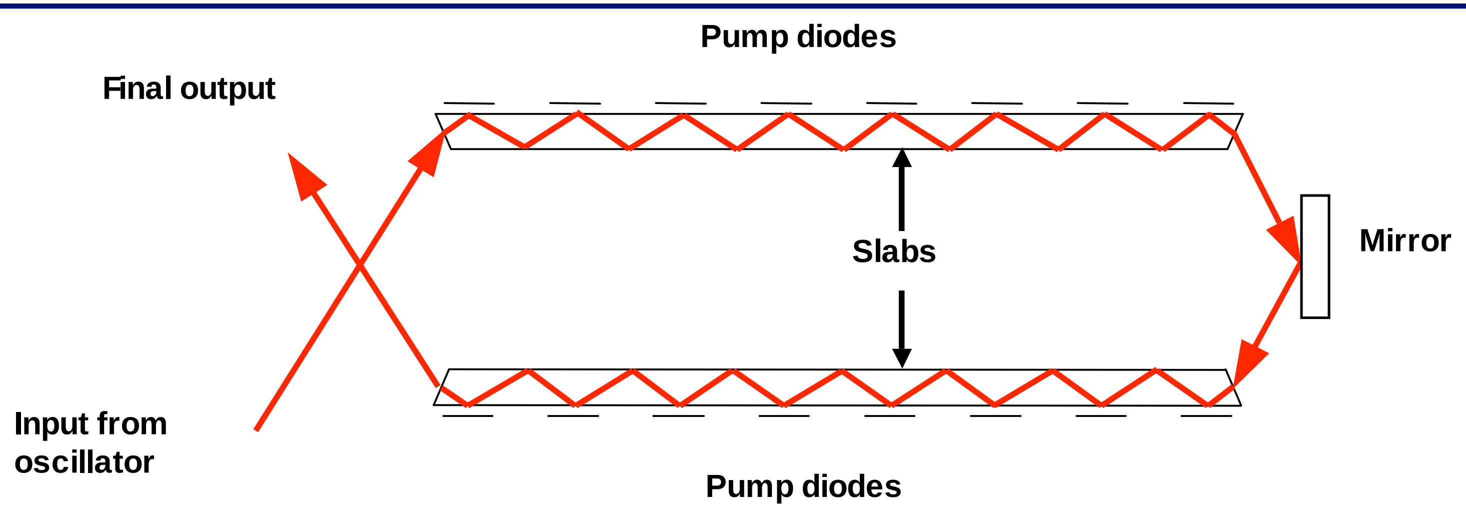
Dual 2-sided pumped amplifiers meet the requirements of most space-based direct detection wind lidars designs

Design of Amplifiers 1 & 2

Single-Sided Pumped and Cooled Amplifier Design

Performance Features

� Diode Pumped	Increased efficiency / Reduced size - weight
� Near Normal incidence	Simplifies AR coatings
� Pump on bounce geometry	High gain fill factor, high efficiency
� Conduction cooled	Elimination of circulating liquids / increased MTBF



Amplifier 1&2: Simulation and Test Results

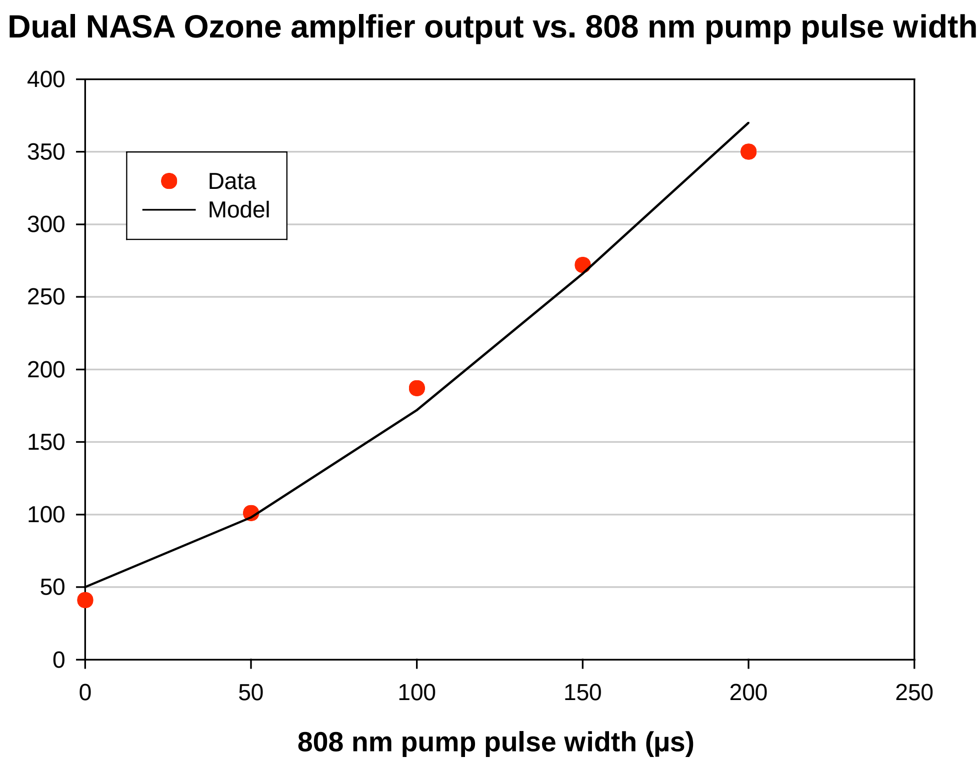
Modeled vs. Measured Results Validate Modeling Approach

Based on a simple Franz-Nodvic amplifier approach

Oscillator Configuration
- **100 μs pump pulse**
- **55 W/bar**
- **100 bars**

Oscillator Output
- **50 mJ/pulse**
- **0.41 cm x 0.41 cm square beam**
- **$M^2 = 1.2$**

Amplifier Configuration
- **Vary pump pulse width**
- **55 W/bar**
- **112 bars/amp**

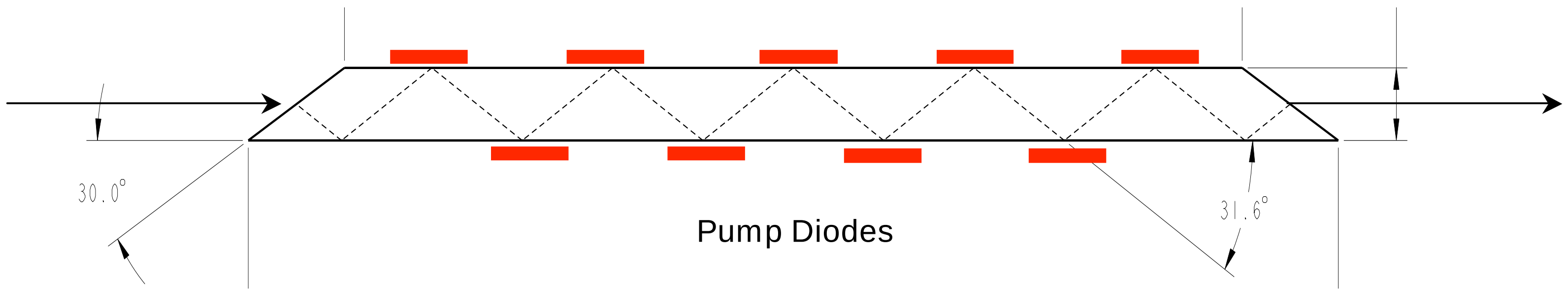


Application of model to the use of higher power pump arrays (40 mJ TEM_{00} input, 75 W/bar, 200 μs pump pulses) predicts over 500 mJ/pulse output

Amplifier 3 Design

2-Sided Pumped Brewster Angle Slab Design Features

_ Brewster angle design	Simplifies optical alignment, only single passed
_ Mature technology	Reduces risk, based on synthesis of previously developed pump on bounce and Brewster angle designs
_ Reduced tendency for parasitic oscillation	Parasitic control in Brewster slabs is well established
_ Pump on bounce geometry	Allows good beam overlap with high gain regions with minimal diffraction effects



Design is a synthesis of Brewster angle and pump on bounce approaches

Amplifier 3 Testing

Power Amplifier Extraction Results

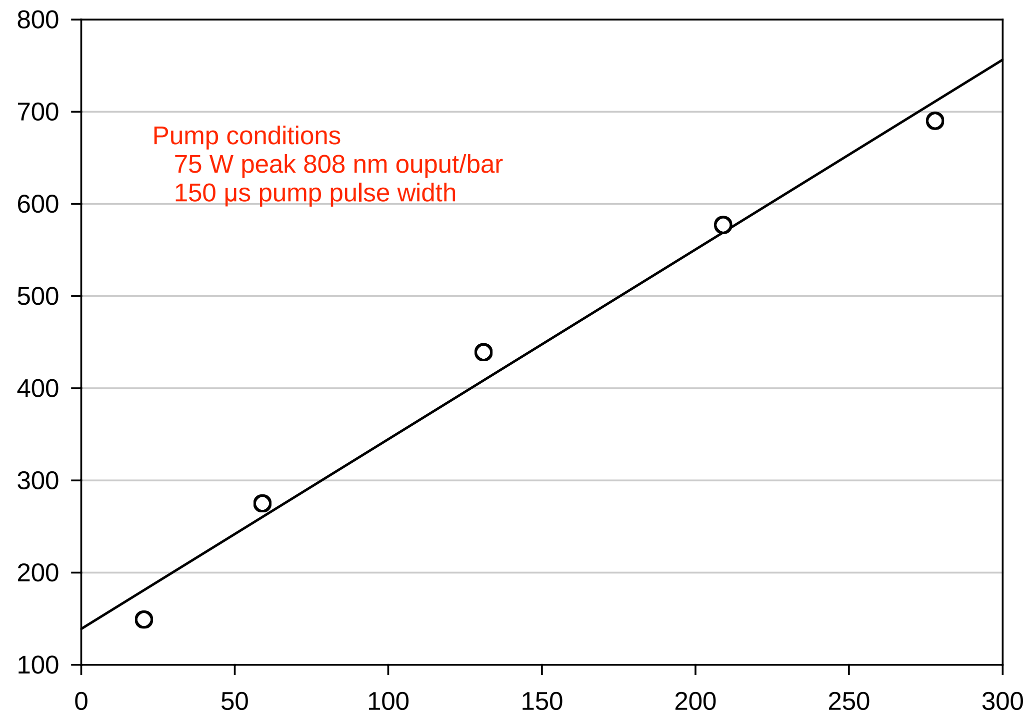
Used output of amplifiers 1 & 2 s input to amplifier 3

- � TEM_{00} ring configuration with 30 mJ output
- �Dual 1-sided pumped amplifiers with only 55 W peak 808 nm output/bar

Measured output of power amplifier vs. input from NASA Ozone system

- �75 W peak 808 nm pump/bar
- �150 µs pump pulse

Measured Input vs.Output for Power Amplifier

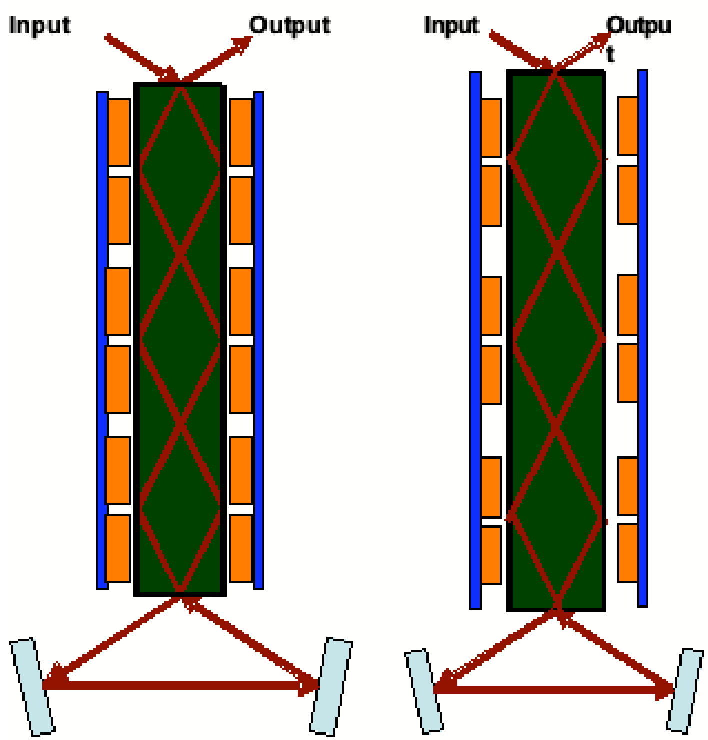


Final amplifier 3 electrical to optical efficiency for 700 mJ output was over 11%. Full system electrical to optical efficiency was over 7%.

Amplifier Design Configuration

3 Bounces-Rectangular Shape-2 sided pumping in the TIR axis, 2 sided conduction cooling, Pump faces uncoated (~10%loss)

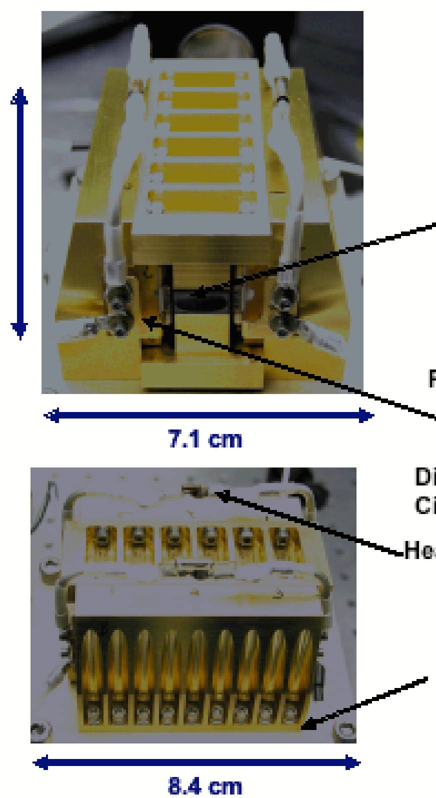
2-Sided Pumped & Cooled Amplifier



First Stage

Second Stage

Prototype Two -Sided Pumped and Cooled Head Design

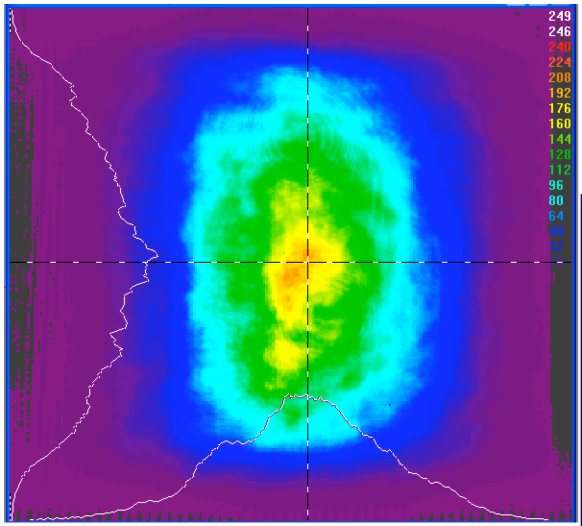


Dimensions	6.8 x 13.0 x 75.3 mm3
Incident Angle	Near Brewster (*57°*)
Extraction	100% at full aperture
Aperture	11.5 x 6.8 mm2 (*internal*)
	7.1 x 6.8 mm2 (*external*)
Doping Level	0.5 ± 0.1 % Nd3+
Pump Diodes	192 ea. 50 watt QCW bars
	(12 ea. 16 bar arrays)

Amplifier 3 Testing

2-Sided Brewster Amplifier Beam Quality and Profiles

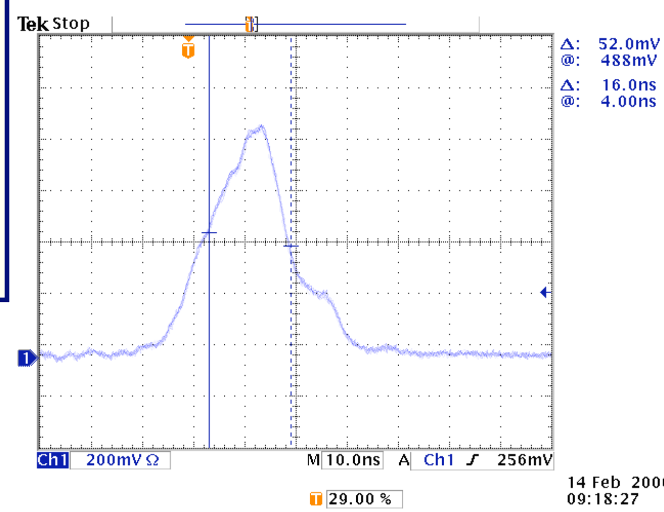
Near field beam profile



- Preliminary M^2 measurements found a value of ~2 for final amplifier output
- Near field spatial is a rectangular super gaussian
- Beam asymmetry in final system is reduced by fine tuning the cylindrical compensating lens values

Typical Pulsewidth

FWHM Pulsewidth is ~16 ns

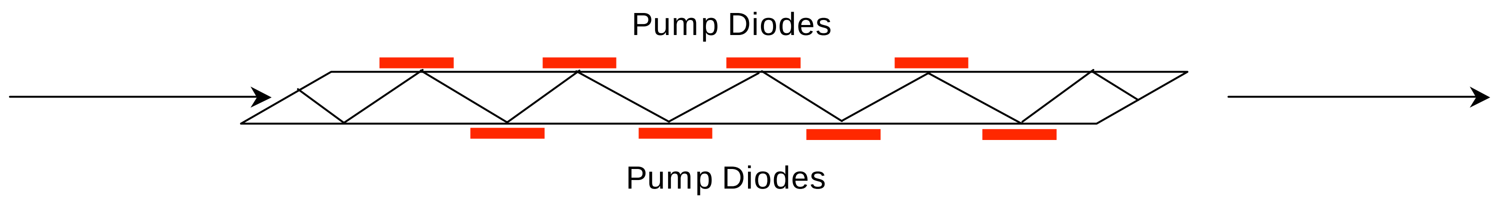


Design achieved the desired goals of high effective fill factor and extraction efficiency with minimal beam quality degradation due to diffraction from the slab edges

Amplifier 4 Design

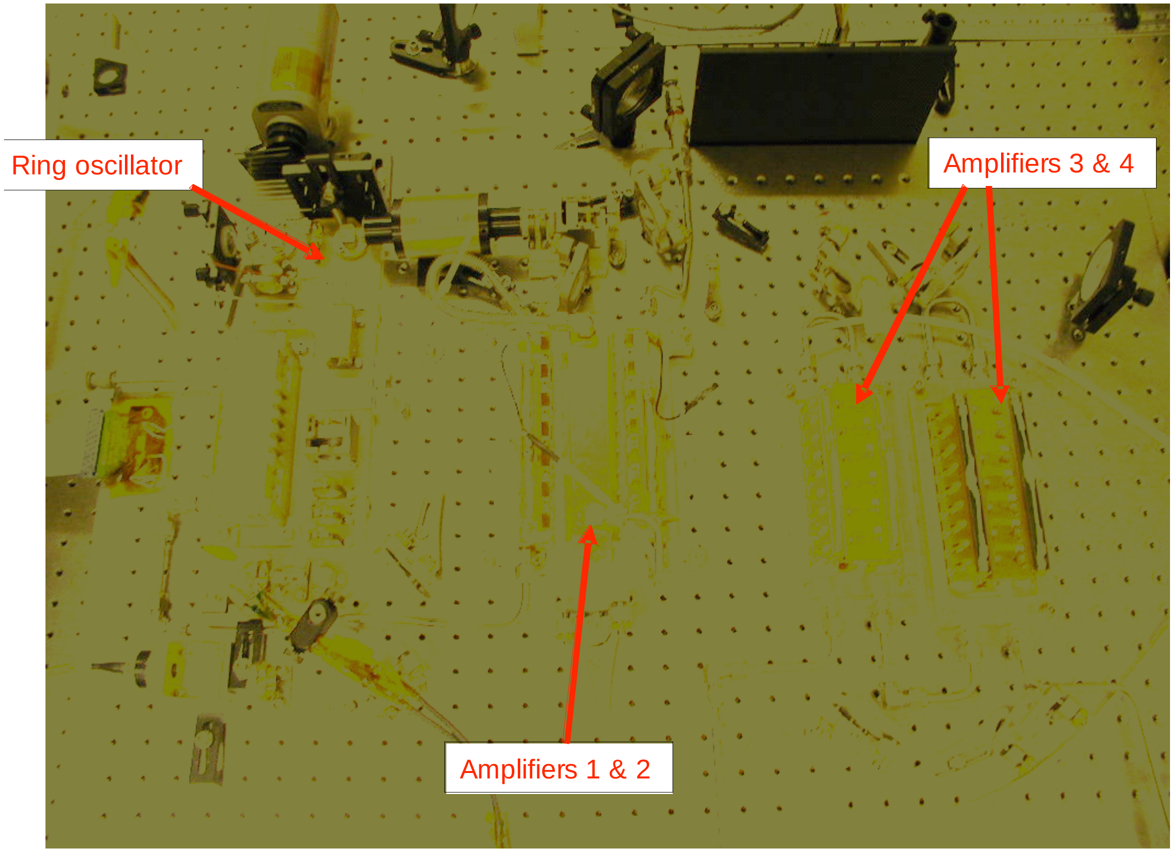
2-Sided Pumped Brewster Angle Slab Design Features

- **Even bounce Brewster angle design reduces beam pointing change due to slab movement**
- **Equal number of arrays per string (4) simplifies diode driver electrical design**
- **Increased cross section of 10x10 mm allows 1 J pulse energy with beam fluence of < 2.5 J/cm^2**
- **From the prototype amplifier measurements we project that over 500 mJ/pulse can be extracted from the final amplifier design**



Modeling predicts that extracting the amplifier 4 with the 700 mJ can achieve ~1.2 J/pulse

Final Optical Layout



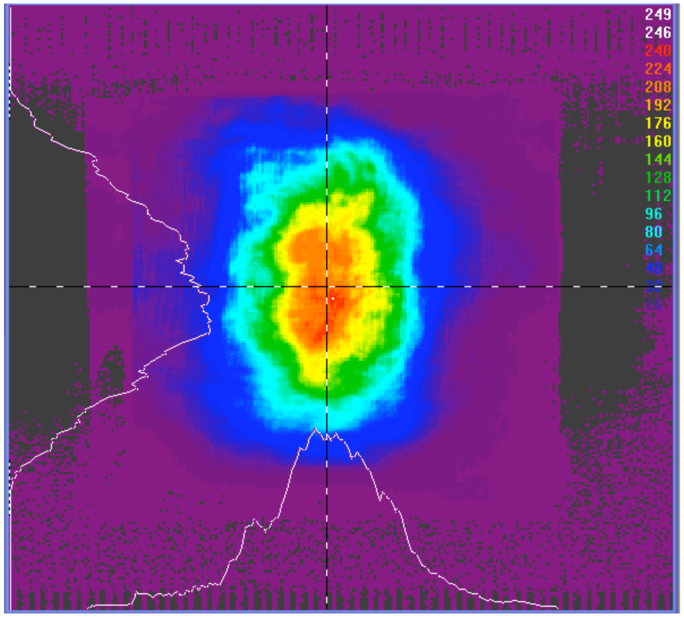
The ring resonator and original dual head amplifier have been integrated onto the final optical bench

Diode Bars and slabs are conductively coupled to the heat sink.

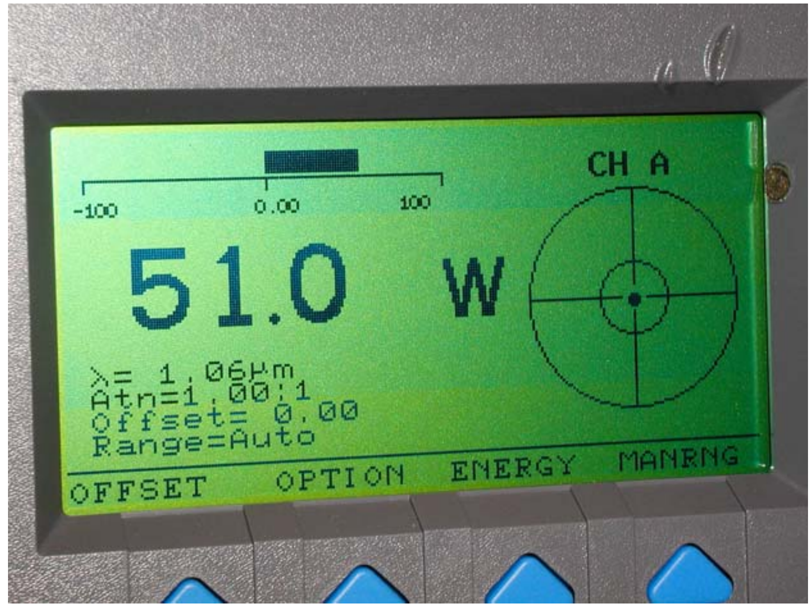
For lab demonstration purposes, the heat sink is cooled by water chillers

For space applications, one can use heat pipes or radiators in lieu of water chillers like in the current CALIPSO laser

Full System Results
Beam Profile & Energy



Near field beam profile of final amplifier output



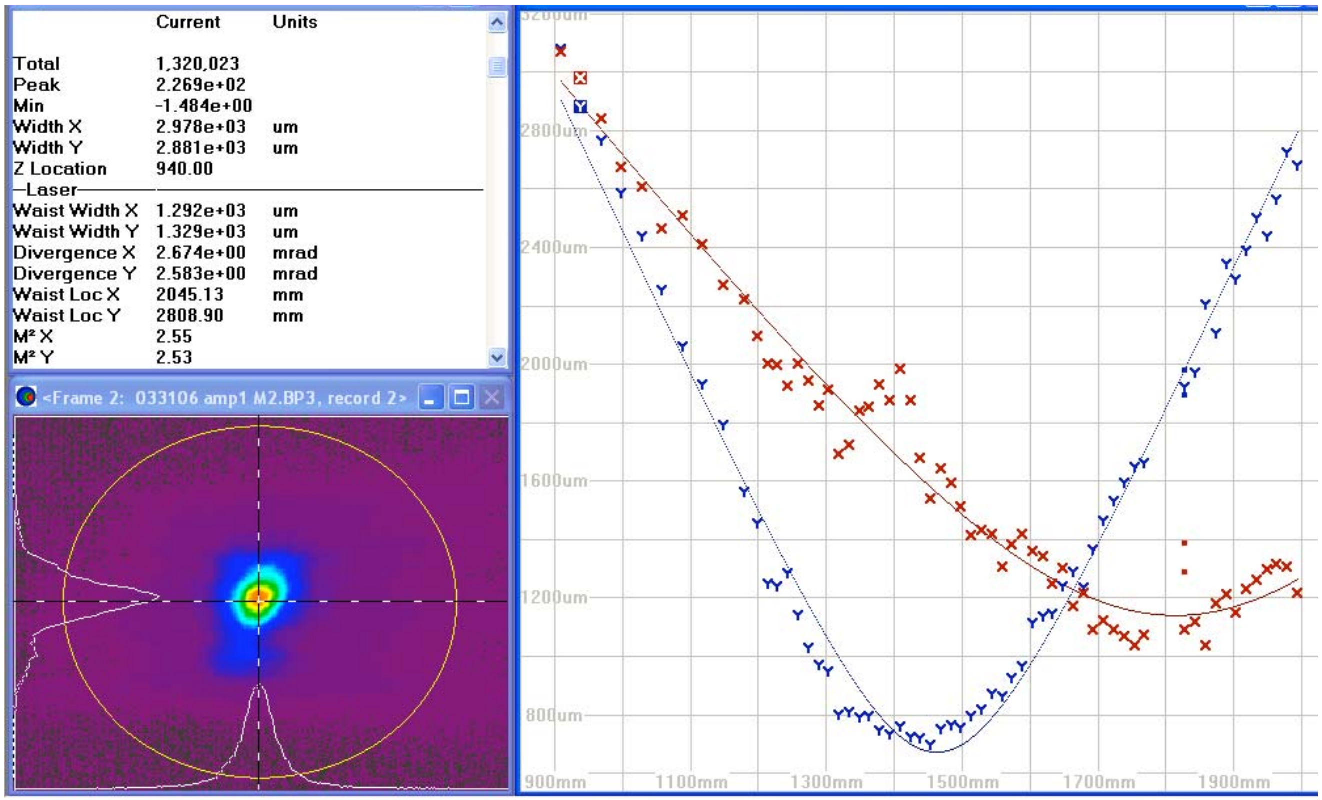
Average power at 50 Hz of 51.0 W (1020 mJ/pulse) for an input electrical power to all pump diodes of 724 W

1020 mJ/pulse and an electrical to optical efficiency >7% was achieved with only 58 W peak power per diode bar pumping the amplifiers
The final pulsewidth was 22 ns

Full System Results: Beam Quality

50 Hz, Full power beam quality measurements

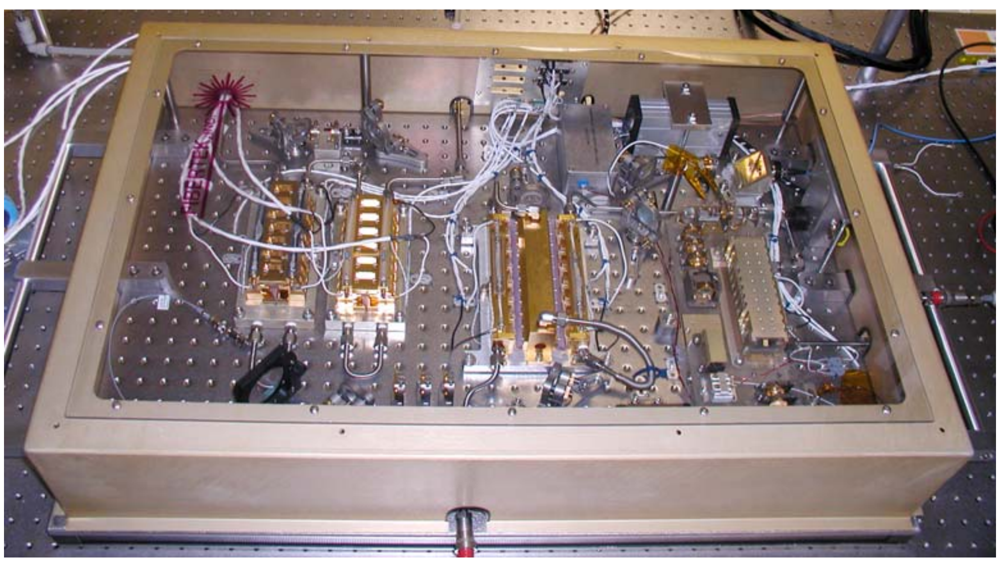
$M_x^2 = 2.5$, $M_y^2 = 2.5$,



Prototype Pump Laser Unit

- **Output Energy** — **~1.1 J/pulse**
- **Pulsewidth** — **= 22 ns**
- **PRF** — **= 50 Hz, (100 Hz possible)**
- **M^2** — **~ 2.5 @ 1.1 J/pulse and 2 @ 700 mJ/pulse**
- **Spatial Mode** — **= Rectangular Super Gaussian**
- **Operation** — **= Any combination of amplifiers can be selected for operation**

Turn-key Pump Laser Unit



Control Electronics Box

Summary and Conclusions

- An all solid-state Nd:YAG Pump Laser has been developed for pumping an UV Converter
  - > 1J/pulse at 50 Hz and 16 ns has been demonstrated
- Pump laser integration with UV converter is progressing
- Currently a brassboard technology demonstration
  - System can be engineered for compact packaging

UV Converter Refinements

Goal: To optimize conversion efficiency and beam quality for high energy
Solution: Use bigger RISTRA module and optimize seeding technique

RISTRA OPO to generate
>200 mJ/pulse at 803 nm

Current RISTRA OPO that
generates ~150 mJ/pulse at 803 nm

Will accommodate larger beam diameters to keep the fluence <1 J/cm^2
The plan is to use a BBO OPO instead of KTA OPO due to higher radiation resistance

On Going and Planned Tasks at SNL

- Reconfigure current experimental setup and develop suitable methods required for pulsed seeding the 803 nm OPO at the idler wavelength of 1576 nm
  - Develop CW-seeded one-crystal KTA RISTRA (Rotated Image Singly Resonant Twisted RectAngle) OPO to generate approximately 5 mJ of 1576 nm light to seed the 803 nm OPO at the idler wavelength
  - Perform 1576 nm Gaussian-to-flattop refractive beam shaping Experiments.
    - Requires redesign of optical breadboard to accommodate original 803 nm OPO plus additional 1576 nm light source

On Going and Planned Tasks at SNL (Contd…)

- Develop methods to lock 803 nm OPO to non-resonant 1576 nm seed pulse
  - The plan is to utilize cavity buildup time
- Following successful implementation of pulsed idler seeding, begin measurements to determine if extra-cavity amplification of 803 nm signal beam from OPO is still required. Ideally amplification will be eliminated.
  - If amplification is required, begin measurements and numerical modeling to optimize amplification
- Following amplification tests, begin measurements and numerical modeling to optimize sum-frequency generation efficiency.
- Replace type-II KTP crystals used for 2ω generation with walkoff-compensated type-I BBO for maximum optical-to-optical efficiency of entire UV generation system
- Measure improvements in overall system efficiency.